TECHNICAL NOTE
D-18

TWO TECHNIQUES FOR DETECTING BOUNDARY-LAYER TRANSITION IN FLIGHT AT SUPERSONIC SPEEDS AND AT ALTITUDES ABOVE 20,000 FEET

By John G. McTigue, John D. Overton,
and Gilbert Petty, Jr.

High-Speed Flight Station
Edwards, Calif.

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION

WASHINGTON August 1959

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION

TECHNICAL NOTE D-18

TWO TECHNIQUES FOR DETECTING BOUNDARY-LAYER TRANSITION IN FLIGHT AT SUPERSONIC SPEEDS AND AT ALTITUDES ABOVE 20,000 FEET

By John G. McTigue, John D. Overton, and Gilbert Petty, Jr.

SUMMARY

Two techniques are presented which make it possible to locate transition on an aircraft during flight. In one method several resistance thermometers were attached to the wing of a supersonic fighter-type airplane. These thermometers were electrically connected to internal-recording circuitry to record a chordwise picture of the boundary-layer conditions on the surface of the wing.

The other method involved the use of sublimable chemicals to obtain a visual indication of the laminar area. Cameras were utilized to record the sublimation process during flight. The sublimation process is ideal for steady-state flight conditions, and also detected protuberances which were causing transition wedges to form ahead of the resistance thermometers used for steady- and maneuvering-flight conditions.

The two techniques proved to be compatible and complementary when used concurrently during steady-state flight conditions.

INTRODUCTION

A flight program was initiated at the NASA High-Speed Flight Station, Edwards, Calif., to extend the range of two available techniques for boundary-layer-transition detection on an airplane. In reference 1 a resistance-thermometer method of transition detection in the Langley low-turbulence pressure tunnel was described and proposed as a method for flight use. Reference 2 describes previous flight work with the sublimation technique at subsonic speeds and altitudes below 20,000 feet. An important asset of each of these methods is that no modification of the aircraft structure is required. With the resistance-thermometer technique a Fiberglas cloth laminate is installed on the wing and used as a filler to provide a smooth surface about the detectors. The sublimation technique requires only that the area be suitable for applying the chemical and that the same area be covered by an in-flight camera to enable correlation of the sublimation process with other test data.

This paper deals with the extension of these two methods of detecting and recording transition on full-scale aircraft in flight to a Mach number of 2 and an altitude of 55,000 feet.

SYMBOLS

A sensitivity of galvanometer (amperes/inch deflection)

D measured algebraic deflection of the oscillograph film above or below the zero position

E battery voltage supplied to bridge

e_0 open-circuit bridge output voltage

F fraction of I_t flowing through galvanometer, I_g/I_t, $\dfrac{R_d}{R_d + R_g}$

I_g current through galvanometer

I_t total current flowing in recording circuit

R_a sensitivity resistance (adjustable)

R_b bridge or source resistance

R_d galvanometer damping resistance

R_g galvanometer coil resistance

R_r reference BN-1 resistance-thermometer resistance

R_s resistance of any sample BN-1 resistance thermometer

R_t total-output-circuit resistance

R_1, R_2 internal fixed resistance of control box

PROCEDURE

Resistance-Thermometer Technique

The resistance-thermometer technique is based on the principle that the heat-transfer coefficient is greater for a turbulent boundary layer than for a laminar boundary layer. It was shown in reference 1 that by utilizing a number of resistance thermometers located along an airplane wing, as in figure 1, the chordwise location of the laminar and turbulent boundary layers could be obtained. The detectors are electrically heated above the boundary-layer temperature and dissipate heat at a rate determined by the boundary-layer heat-transfer coefficient. Detectors in the laminar boundary layer dissipate heat at a lower rate than those located in the turbulent boundary layer. The lower rate of heat dissipation causes the laminar detectors to be hotter and to have a higher electrical resistance than the detectors in the turbulent region.

Eleven resistance-thermometer elements of the Ruge-de-Forest Stikon BN-1 type were installed on the top and bottom surfaces of an airplane wing (fig. 1). To isolate these elements thermally from the wing, they were embedded in a bakelite carrier, which was used so that a machine tolerance of ±0.002 inch could be maintained on the insulation thickness between each resistance thermometer and the wing skin, as shown in the insert of figure 1. The carriers were bonded to the wing surface with Armstrong A-6 cement containing a 0.001-inch-thick Fiberglas cloth. The cement was allowed to cure under a pressure of approximately 10 psig (fig. 2).

The resistance thermometers were connected to a terminal strip on the wing tip by No. 26-gage enameled copper wire, which was selected because of the ease of installation in the thin laminate. The recording circuitry (fig. 3) was electrically connected to the terminal strip with 22-gage wire to minimize wire resistance. The forward ten BN-1 elements of each wing surface were the fourth arms of two-active arm bridge circuits. The second active arm of the bridge circuits was the eleventh, or reference, element on each surface. The reference effectively cancels the tare-temperature effects up to a known flow condition and thus increases the sensitivity and resolution potential of the circuitry. By choosing a turbulent flow for the reference, it was relatively simple to assure a known condition. Carborundum boundary-layer trips were placed upstream from the reference resistance thermometer so that the thermometer would be in a turbulent flow at all times. Subsequent flights using the sublimation technique indicated that the reference remained in a turbulent area, and the carborundum was then removed. This system will operate just as effectively if the reference is located in a laminar-flow condition, but, it is difficult to assure laminar flow at a fixed location under all flight conditions. The resistances of the other ten elements would be either higher than, or about equal to, the reference, depending on the boundary-layer flow over them.

Figure 3 shows the recording circuitry for multiplexing the ten sample elements on one channel of a recording oscillograph so that the signal trace records a picture of the actual boundary-layer condition over the wing. Figure 3 also illustrates the method by which the system sensitivity can be adjusted so that maximum resolution can be recorded for each flight condition.

To make certain that the operating temperatures of the boundary-layer-detector elements were above the adiabatic wall temperature, it was necessary to know the detector temperature. Therefore, a temperature-sensing BN-1 monitor was inserted just beneath a twelfth resistance thermometer in a common bakelite carrier (insert of fig. 1) to measure the temperature of the twelfth resistance thermometer exposed to the boundary layer. Correlation between this monitor temperature and the temperature of the reference element was experimentally determined to be within 4 percent. The recording circuitry of the temperature-sensing BN-1 monitor is shown in figure 4.

The following procedure was used to calibrate the temperature-sensing system:

1. BN-1 resistances corresponding to various temperatures were taken from a table derived from Army-Navy Specification (MIL-B-5495) for BN-1 elements.

2. These resistances were set on a precision decade-resistance box and were substituted into the control box in place of the BN-1 elements while an oscillograph record was taken.

3. The cockpit calibrate switch was closed while the oscillograph was operating in order to obtain a calibrated deflection on the film.

4. Calibration curves were plotted from the oscillograph record and were used to reduce the flight data. Deflection corresponding to temperature was divided by the deflection caused by the calibrate, and the quotient was plotted against temperature. A plot of this type is used to cancel errors caused by change in battery voltage and sensitivity change in the galvanometer.

After determining the in-flight resistance of the BN-1 element, the temperature of the element corresponding to that resistance can be read from a standard AN (Army-Navy) curve for BN-1 elements (fig. 5). The following equation is used to determine the in-flight resistance of any resistance-thermometer element:

$$R_s = \frac{EFR_rR_2 + DAR_tR_2\left(R_r + R_1\right)}{EFR_1 - DAR_t\left(R_r + R_1\right)}$$

Development of this equation is given in detail in the appendix.

A Fiberglas cloth laminate was used to build up the surface flush with the top of the BN-1 element carriers, thus forming a glove over the wing. The wing glove was constructed by applying several layers of Fiberglas cloth and by brushing an epoxy compound over each layer. Bakelite Co. epoxy resin No. ERL-2795 and hardener No. ERL-2807 were used to make the compound. The compound used on the leading edge of the wing was a combination of Applied Plastics Co., Inc., epoxy resin No. 410 and hardener No. 180. A mixture of 1 percent cabosil and 99 percent epoxy resin was used on the lower surface of the wing to increase the viscosity of the mixture, thus minimizing dripping and running.

An Electro Products Labs., Inc., electronic dynamic micrometer was used to measure the thickness of the glove laminate, which was maintained at 0.100 ±0.005 inch. Final finishing of the laminate was accomplished by rasps, handsanders, and pneumatic buffers. The average surface finish of the laminate, measured with a Brush Electronic Model BL-110 "Surfindicator," was 7 microinches.

Sublimation Technique

The sublimation technique is dependent upon several factors. The greater heat-transfer coefficient in the turbulent boundary layer results in higher surface temperatures than in the laminar boundary layer (excluding the stagnation temperatures on the wing leading edge). This elevated temperature and the thickening of boundary layer at the location of transition, with the resulting increase in the volume of the boundary layer, causes a suitable chemical to increase its rate of sublimation in the turbulent region with respect to that of the laminar region. Because of this increased rate of sublimation, the chemical in the turbulent area is removed before the chemical in the laminar area has been appreciably affected. The indication of the laminar area is then shown by the chemical remaining.

Various chemicals have been flight-tested to determine their applicability to transition detection by sublimation. These chemicals, their formulas, melting temperatures, and vapor pressures at specific temperatures, as obtained from reference 3, are listed in table I. Table I and figure 6 are presented as an aid in choosing chemicals for particular applications. The information shown in figure 6 was taken from reference 3, plotted, and extended by a straight-line extrapolation to the lower vapor pressures.

The success of the sublimation technique was found to depend on the method of applying the chemical, as well as upon the chemical and solvent used. Petroleum ether was chosen as the solvent so that no reaction would take place with the previously applied paint and the sublimation solution. Good results were produced with a Devilbiss-type MBS spray gun with a No. 30 cap and an AV-15-EX fluid head. A fan-type spray pattern using a gage pressure of 45 psi gave the desired consistent coverage. To obtain a satisfactory uniform coating and to prevent fading of the chemical before the airplane was airborne, it was necessary to apply three to four coats of the chemical. The first coat was applied in a direction parallel to the airstream. Subsequent coatings were formed by passing the spray gun at a 90° angle to each previous coat. Approximately 12 inches was found to be the optimum distance between the spray nozzle and the surface to be coated. This distance permitted the solution to contact the surface in a slightly damp condition. Upon evaporation of the solvent, the roughness size of the chemical particles was a minimum, and the particles readily adhered to the surface.

It should be emphasized that although satisfactory results were obtained with the above procedure, it was necessary to use extreme care in the application of the solution. Improper application could result in large particles remaining which could adversely affect transition.

To facilitate correlation of the sublimation process with other flight parameters, cameras were mounted in such a way that in-flight motion pictures could be taken of the areas covered with the subliming chemicals (fig. 7). Color film was utilized to bring out the contrast. Standard NASA film-recording instrumentation was used to record airspeed, altitude, angle of attack, and angle of sideslip. Correlation between the camera film and other recorded data was accomplished by a standard timer and a synchronous film recorder.

RESULTS AND DISCUSSION

During approximately 40 instrumented flights, boundary-layer transition was detected by using the sublimation and the resistance-thermometer techniques separately and concurrently.

Tests with various battery voltages showed that 30 volts heated the elements enough above the adiabatic wall temperature to detect transition to a Mach number of 2. Because the BN-1 elements would overheat, it was necessary to use extreme caution to insure that the voltage was not applied before the airplane was airborne.

The present system was not designed for a measure of boundary-layer temperature, but to obtain a close estimate of heated BN-1 temperatures in flight. In-flight measurement of the boundary-layer temperature could have been obtained with the resistance thermometers by changing the bridge circuitry. This would be a more accurate temperature measurement than the method used in the present installation.

The BN-1 resistance thermometer can be operated at 350° F. By eliminating the air bubbles in the laminate, the resistance-thermometer system can be used to detect transition up to a Mach number of 2.30, provided the various BN-1 elements are not located in the stagnation region. These air bubbles, which invariably form during installation of the laminate, could be removed by applying a partial vacuum to the laminate while it is curing. When the boundary-layer temperature reached approximately 200° F, the bubbles expanded and ruptured the surface. The small holes caused by the rupture were filled with new epoxy resin from a hypodermic needle, and the surface was refinished by the process previously described.

The response of the resistance-thermometer detectors was rapid enough so that they could be used to detect the location of transition during transient- as well as steady-flight conditions. The sublimation technique was used to detect transition during steady-state-flight conditions because only one indication was given for each coating of the chemical. Since the data from the resistance thermometer substantiated the expected indication of the boundary-layer transition, which was determined by inspection of the oscillograph record, it was only necessary to measure film deflection when an actual temperature check was desired. (See insert in figure 3 for typical oscillograph trace.) In many cases sublimation patterns aided in explaining unfamiliar oscillograph traces. Turbulent wedges, originating upstream of the detectors, caused local areas of turbulent flow. As can be seen in figure 8, the third detector indicated turbulent flow in an area that would otherwise be laminar.

The transition from laminar to turbulent flow is a sudden phenomenon, but the point of transition oscillates over a length of flow, referred to as the transition region. Within this region the heat transfer varies from the relatively low value associated with laminar flow to the higher value for turbulent flow. Detectors within this region did not respond to give the abrupt deflection indicated in figure 8, but indicated a gradual change from laminar to turbulent flow. The extent of laminar flow and the beginning of fully developed turbulent flow is identified on the record at the relative maximum and minimum galvanometer deflections, respectively. On occasions, an abrupt change in the galvanometer deflection would appear as a result of irregular flow patterns and the spacing of the detectors.

As can be seen in figures 8 and 9, the resistance thermometers did not cause transition. Therefore similar applications need not correspond to the spacings and locations used for this installation.

In addition to giving a visual indication of the transition along the wing, sublimation was used to detect minute nicks or protuberances in the Fiberglas so that it could be maintained in the best possible state of repair. It should be noted that once the desired finish for the glove had been attained, this condition was easily maintained.

The applicability of the sublimation technique to clean, unpainted wings and to painted wings was determined by conducting a series of sublimation tests on the left wing both in the unpainted and the painted condition. Figures 10 and 11 show the left wing in the painted and unpainted conditions, respectively, after sublimation flights. Since the left wing was painted completely black, the sublimation was more easily seen because of the sharp color contrast. Once it had been determined that the technique was satisfactory, the painted left wing was used as a reference by the pilot to judge the rate at which sublimation was progressing.

Possibly, better results could be obtained by dying the Fiberglas laminate black upon installation so that the contrast between the chemical and the laminate would obviate the need for using the other wing as a reference. As will be noted in figures 10 and 11, some of the sublimable chemical along the wing-fuselage juncture and in the rear portions of the wing did not sublime. This is caused by large structural members and mechanisms which act as heat sinks, thus preventing the wing skin from attaining temperatures high enough to cause a high rate of sublimation.

To improve upon and to extend the sublimation technique used in reference 2 it was necessary to make numerous exploratory flights to the desired test conditions with various chemical compounds applied to the test surface. The flights showed that the best indications occurred when the conditions were such that the adiabatic wall temperature caused the vapor pressure of the chemical to be from 0.01 mm to 1.00 mm of mercury. An average of 3 minutes at the test conditions was required for the indication to occur, as presented in table II for the indications shown in figures 9 to 14. If test conditions could be maintained for a longer period of time, chemicals with lower vapor pressures could be used. Chemicals of higher vapor pressures could be employed if test conditions could be reached before the sublimation process begins. The time required will vary greatly, depending on the chemical used; therefore, no attempt is made to predict the suitability of chemicals other than those tested.

The results shown in table II were obtained with fluorene and phenanthrene. The other chemicals listed in table I were tested early in the program, with the exception of benzanthrone, carbazole, and hexachlorobenzene, and were discarded as unsatisfactory because they were unsuitable for the desired test conditions or because they afforded poor contrast with the area to be coated.

Benzanthrone, carbazole, and hexachlorobenzene have been tested to a Mach number of 2.2 on other research aircraft. Preliminary results show that these chemicals would work satisfactorily at speeds approaching $M \approx 2.5$, or greater. Figure 6 shows the vapor pressures for these and additional chemicals which may be used to extend the sublimation technique to higher altitudes and Mach numbers.

The chemicals, solvents, and resins used in the two techniques are, more or less, toxic and may be serious fire hazards. Personnel involved in handling, mixing, or applying these compounds should be cautioned regarding the toxic and irritant properties. Protective clothing should be worn and respirators used so that no contact is made between the body and chemicals. Application of the sublimation chemical-petroleum ether solvent solutions should be performed in a well-ventilated area to prevent collection of dangerous concentrations of petroleum fumes (ref. 4).

CONCLUSIONS

Two techniques to detect transition at supersonic speeds were tested to a Mach number of 2.0 and altitudes up to 55,000 feet. One method used several resistance thermometers attached to the wing of a supersonic fighter-type airplane. The other technique utilized a chemical having the property of sublimation. This chemical would sublime in the turbulent region and remain in the laminar region. From the results of this program it is concluded that:

1. The resistance-thermometer and sublimation techniques have been used satisfactorily to detect transition to a Mach number of 2.0 and altitudes up to 55,000 feet.

2. The two techniques give compatible and complementary data.

3. Preliminary results show that these techniques would work satisfactorily at speeds approaching a Mach number of approximately 2.5. The

resistance-thermometer technique can be used for steady-state flight as well as for maneuvering-flight conditions, whereas the sublimation technique can be used only during steady-flight conditions, but gives a visual picture of the complete surface.

4. The sublimation technique is extremely versatile and can be used on any portion of the aircraft that can be photographed during flight.

High-Speed Flight Station,
National Aeronautics and Space Administration,
Edwards, Calif., February 5, 1959.

APPENDIX

ERROR ANALYSIS OF RESISTANCE THERMOMETERS

Under ideal conditions, where all electrical components, resistors, wire length, etc., are equal, no unbalance will be present in the output of the boundary-layer-detector circuit. However, since electrical balance is not usually the case, every possible known cause for error was investigated, with the following results:

1. Each BN-1 element has an off-tolerance resistance at the same temperature. The Ruge-de Forest Co. furnishes the off-tolerance resistance (A factor) of each BN-1 element to the nearest tenth of an ohm. All of the BN-1 elements used on the bottom wing surface had the same A factor of 0.2 ohm. The reference element and two of the ten sample elements on the top wing surface had an A factor of 0.2 ohm. The other eight sample elements had A factors of 0 ohm. Thus, an unbalance due to A factor occurred for these eight elements. The maximum unbalance caused from this error was determined to be about 1 percent with the circuitry used for this application. In a more sensitive application, the A-factor difference could be more pronounced, and an effort should be made to use elements with the same A factor wherever possible.

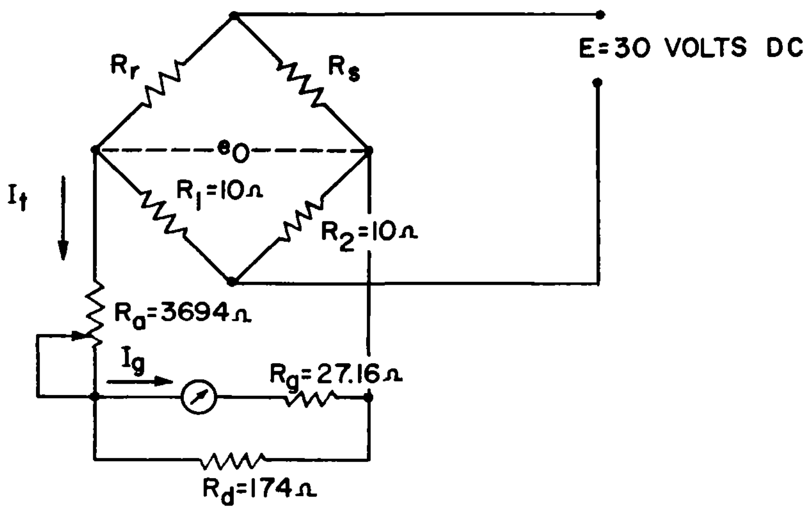
2. It was determined that the No. 26-gage enameled copper wire caused error because of its relatively large resistance and because of the different lengths that were used from the wing-tip terminal strip to the elements. In the most extreme case, the difference in circuit resistance due to wire length caused an unbalance of 2 percent in the output. This is a systematic error which can be corrected in future applications by using equal lengths of a larger gage wire.

3. One assumption for ideal conditions was that all heat dissipated by the heated BN-1 elements would be conducted to the boundary layer. At this time, the error that is introduced into the system due to losses to the wing, has not been determined. In an effort to minimize unequal losses to the wing, close tolerances were held on the insulation thickness.

4. The control box, itself, could cause unbalance because of the off-tolerance in the 10-ohm resistors in each bridge circuit. Wire-wound, 0.1-percent precision, 1-watt resistors were used in this investigation, and tests run on the box verified that the unbalance due to the control box was negligible.

The following set of equations and sample calculations is included to aid in the development of resistance-thermometer installations similar to the installation used in this investigation:

1. The derivation of the BN-1 element resistance equation is shown in the following sketch (see fig. 3 for complete multiplexed circuit).



$$e_0 = \frac{E\left(R_s R_1 - R_r R_2\right)}{\left(R_r + R_1\right)\left(R_s + R_2\right)} \quad \text{(volts)}$$

R_b = bridge output or source resistance $= \dfrac{\left(R_r + R_s\right)\left(R_1 + R_2\right)}{R_1 + R_2 + R_r + R_s}$

$$F = \frac{R_d}{R_d + R_g}$$

$R_t = R_b + R_a + \dfrac{R_d R_g}{R_d + R_g}$ (Assume R_t constant; R_b changes with temperature but has negligible effect on R_t.)

From Thevenin's theorem:

$$I_t = e_0/R_t = DA/F$$

$$\frac{E\left(R_s R_1 - R_r R_2\right)}{R_t\left(R_r + R_1\right)\left(R_s + R_2\right)} = \frac{DA}{F}$$

$$R_s = \frac{EFR_r R_2 + R_t R_2 DA\left(R_r + R_1\right)}{EFR_1 - R_t DA\left(R_r + R_1\right)}$$

2. The errors for a typical flight condition may be obtained as follows:

It was determined, by the process described in the PROCEDURE section, from the monitor temperature sensor that the temperature of the reference element was 274° F. A deflection of 0.200 inch was measured on the recorded data film. Sensitivity resistance R_a was 3693.6 ohms for this example. Thirty volts E was used to heat the element during this flight. The galvanometer sensitivity A was 164.6×10^{-6} amperes/inch.

The resistance of the reference element corresponding to 274° F is 129.0 ohms R_r, and $F = \frac{174}{174 \times 27.16} = 0.865$. Therefore

$$R_s = \frac{30(0.865)(129)(10) + (3735)(10)(0.20)\left(164.6 \times 10^{-6}\right)(129 + 10)}{30(0.865)(10) - (3735)(0.20)\left(164.6 \times 10^{-6}\right)(129 + 10)}$$

R_s = 138.8 ohms

Temperature corresponding to this resistance is 311° F.

3. Assume an A-factor difference of 0.20 ohm in this example on the reference element. The total correction at the operating temperature is 0.30 ohm. Therefore, the reference element resistance will change to 129.00 + 0.30 = 129.30 ohms. This will change the open-circuit output voltage from 142.1 mv (millivolt) to 137.4 mv, or with the system sensitivity, a difference of 0.007-inch deflection, which represents a temperature difference of 3° F or 0.95-percent error.

4. Assuming the same flight conditions and considering the largest error due to difference in measured wire resistance, the reference element resistance would be changed to 129.0 - 1.306 = 127.7 ohms, and the sample element would be changed to 138.8 - 1.108 = 137.7 ohms. This difference would cause an open-circuit voltage output of 147.5 mv, or a difference of 0.007-inch deflection, which represents a temperature difference of 3° F or, again, 0.95-percent error.

REFERENCES

1. Richardson, Norman R., and Horton, Elmer A.: A Thermal System for Continuous Monitoring of Laminar and Turbulent Boundary-Layer Flows During Routine Flight. NACA TN 4108, 1957.

2. Main-Smith, J. D.: Chemical Solids as Diffusible Coating Films for Visual Indications of Boundary-Layer Transition in Air and Water. R. & M. No. 2755, British A.R.C., Feb. 1950.

3. Hodgman, Charles D., ed.: Handbook of Chemistry and Physics. 33rd Edition. Chemical Rubber Publishing Co., 1951, pp. 448-1202, 1937-2017.

4. Sax, N. Irving: Handbook of Dangerous Materials. Reinhold Publishing Corp., 1951.

TABLE I.- PHYSICAL PROPERTIES OF SOME SUBLIMING CHEMICALS

Chemical	Formula	Melting point, °C	Temperature, °C	
			1 mm Hg	40 mm Hg
Acenaphthene	$C_{12}H10_{10}$	95	S	168.2
Azobenzene	$C_{12}H_{10}N_2$	68	103.5	187.9
Fluorene	$C_{13}H_{10}$	113	S	185.2
Napthalene	$C_{10}H_8$	80.2	52.6 S	119.3
Phenanthrene	$C_{14}H_{10}$	100	118.2	215.8
Anthracene	$C_{14}H_{10}$	217	145.0 S	217.5 S
Benzanthrone	$C_{17}H_{10}O$	174	225	350
Carbazole	$C_{12}H_9N$	244.8	S	S
Hexachlorobenzene	C_6Cl_6	230	114.4 S	206.0 S

Note: These properties are obtained from reference 3. The symbol S indicates chemicals in a solid state.

TABLE II.- TESTS OF SUBLIMATION TECHNIQUE ON A SUPERSONIC FIGHTER-TYPE AIRCRAFT

Chemical	Surface covered	Test conditions		Time (min.) to reach test conditions[a]	Time (sec) at test conditions	Time (sec) indication started after test conditions reached	Indication completed, (sec)	Remarks
		Mach number	Altitude, ft					
Fluorene	Upper right	1.8	40,000	17	250	141	247	See figure 12
Fluorene	Upper right	2.0	55,000	22	210	4	118	See figure 13
Phenanthrene	Lower right	1.9	55,000	20	200	50	204	See figures 9 and 14
Phenanthrene	Upper left	2.0	55,000	23	225	54	245	See figure 11
Phenanthrene	Upper left	1.8	53,000	21	205	58	215	See figure 10

[a]Average of 20 minutes from completion of spraying chemical to take-off.

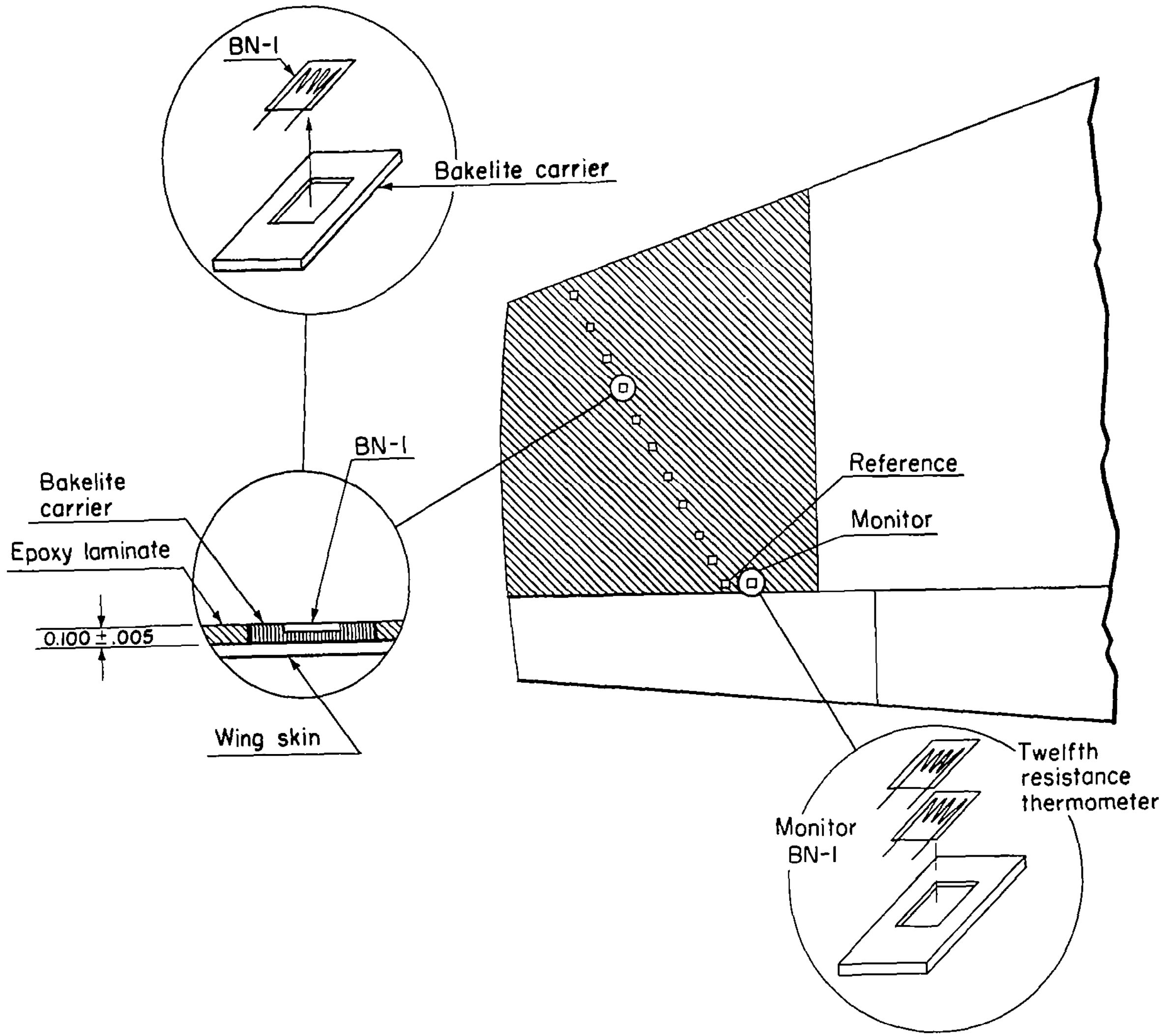


Figure 1.- Detail sketch of installation of BN-1 resistance-thermometer boundary-layer detector.

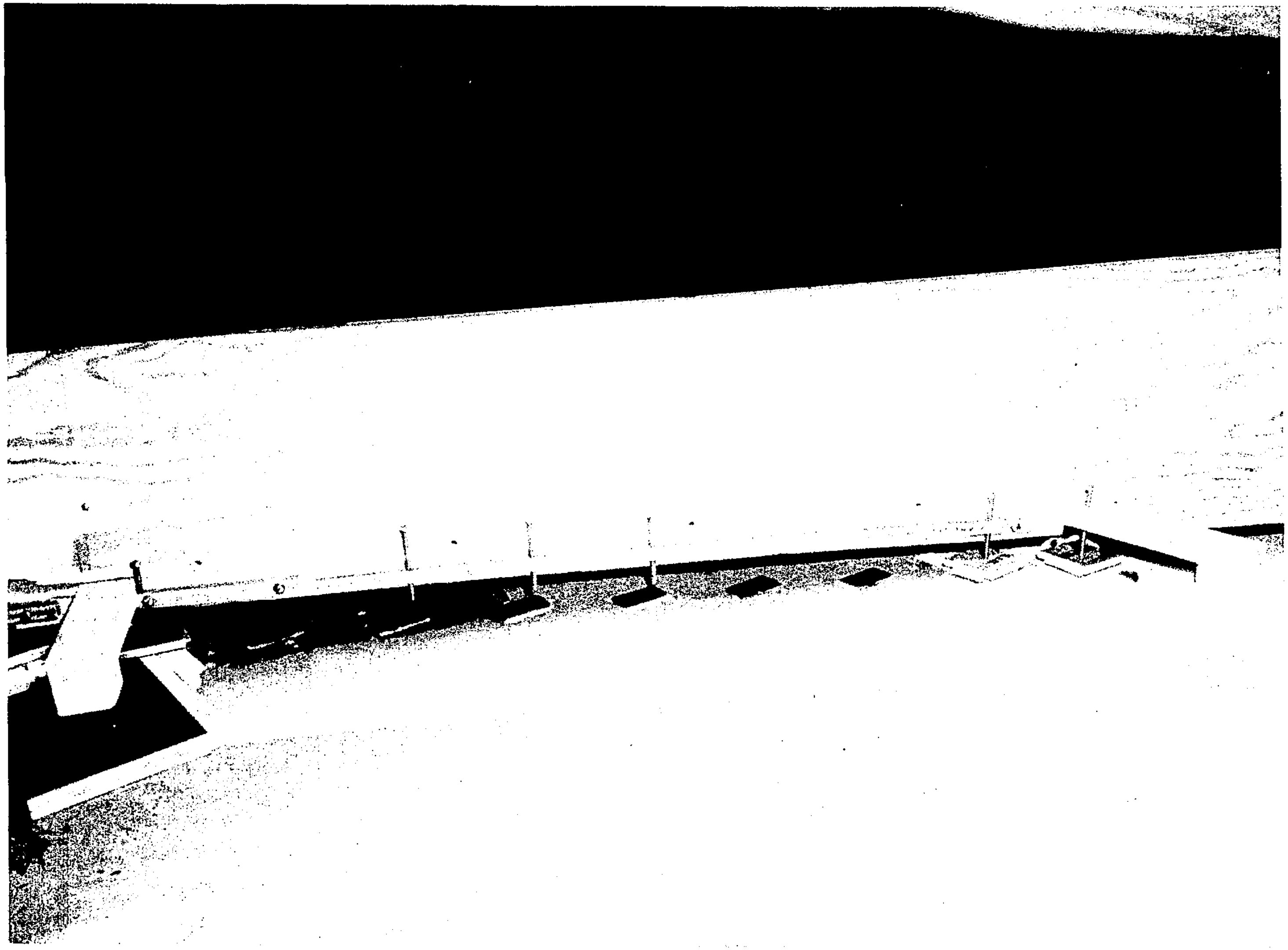


Figure 2.- Applying BN-1 Carriers to wing under a pressure of approximately 10 psig. E-3238

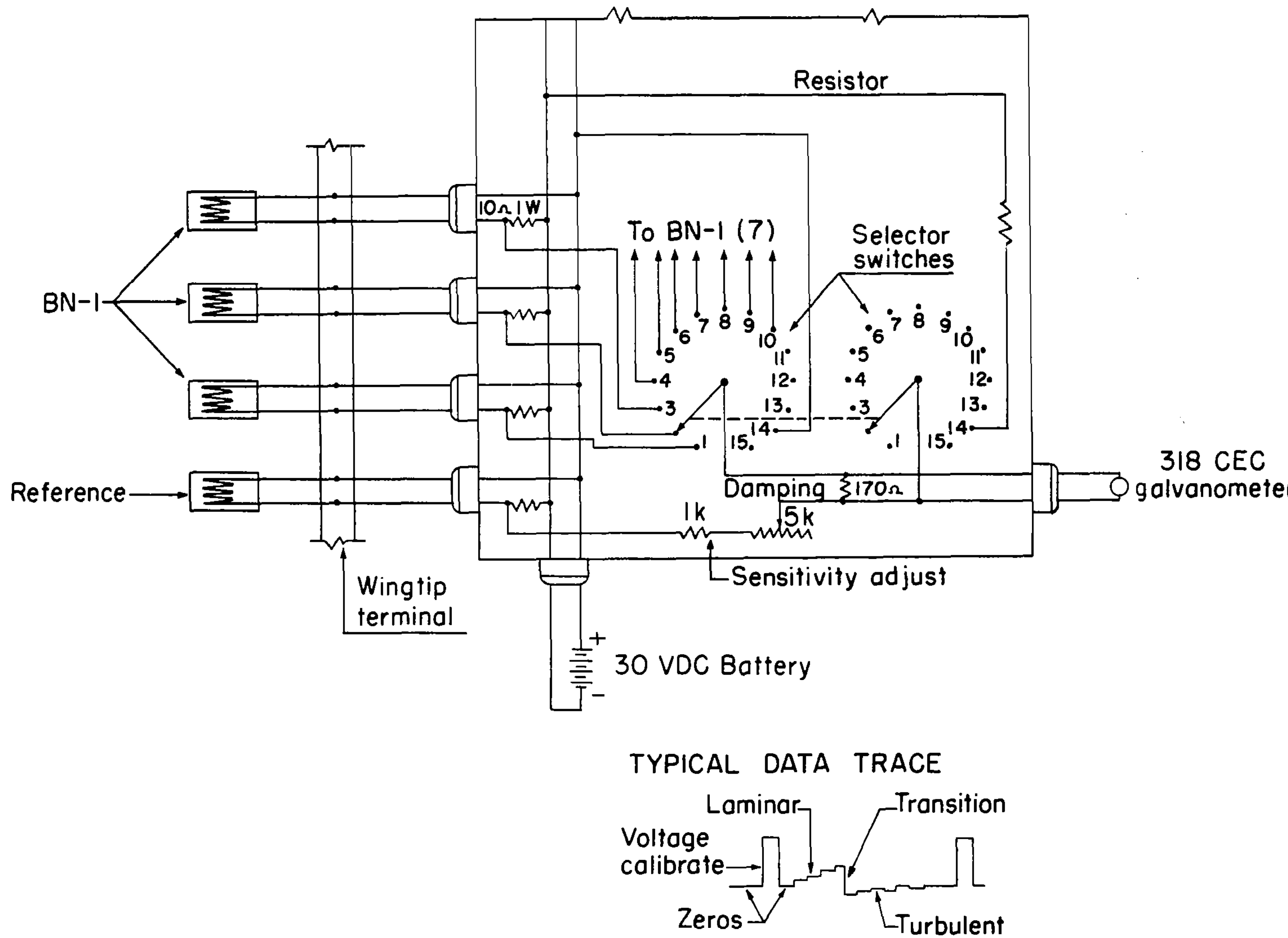


Figure 3.- Diagram of BN-1 resistance-thermometer boundary-layer transition-detection circuit.

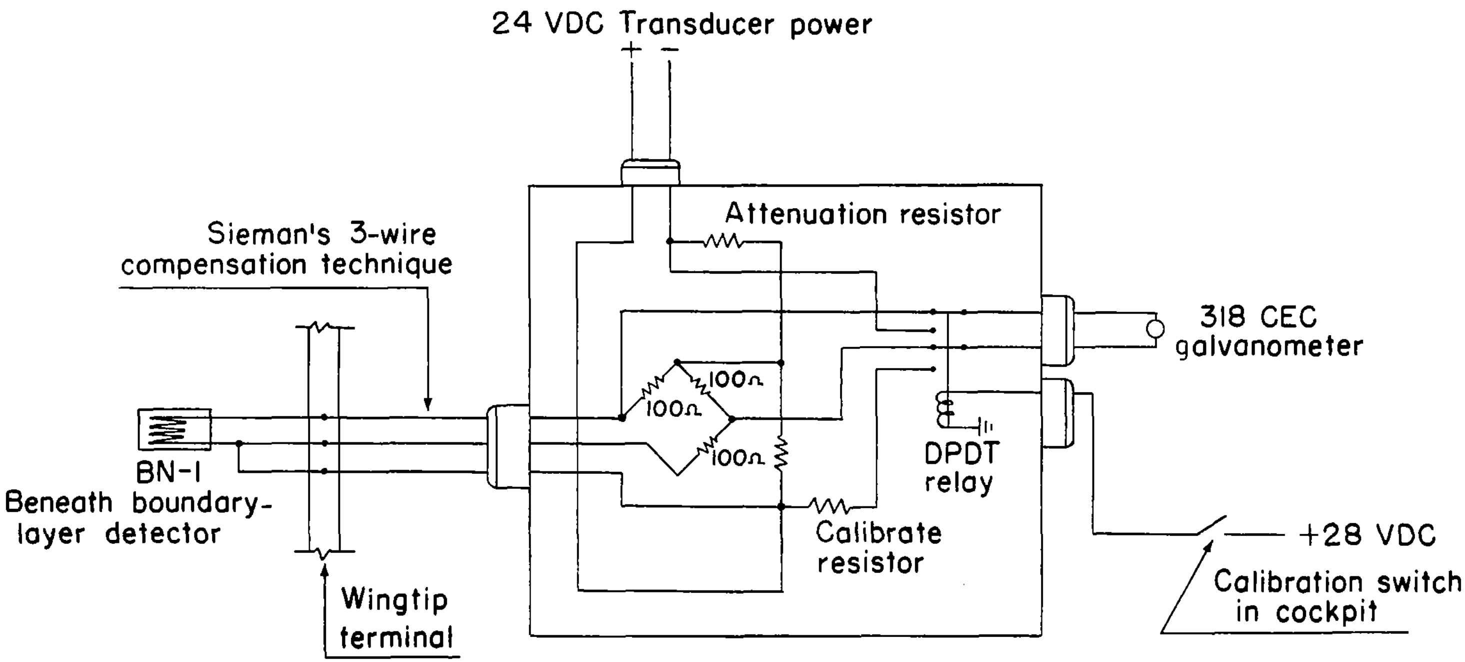


Figure 4.- Drawing of recording circuitry of temperature-sensing BN-1 monitor.

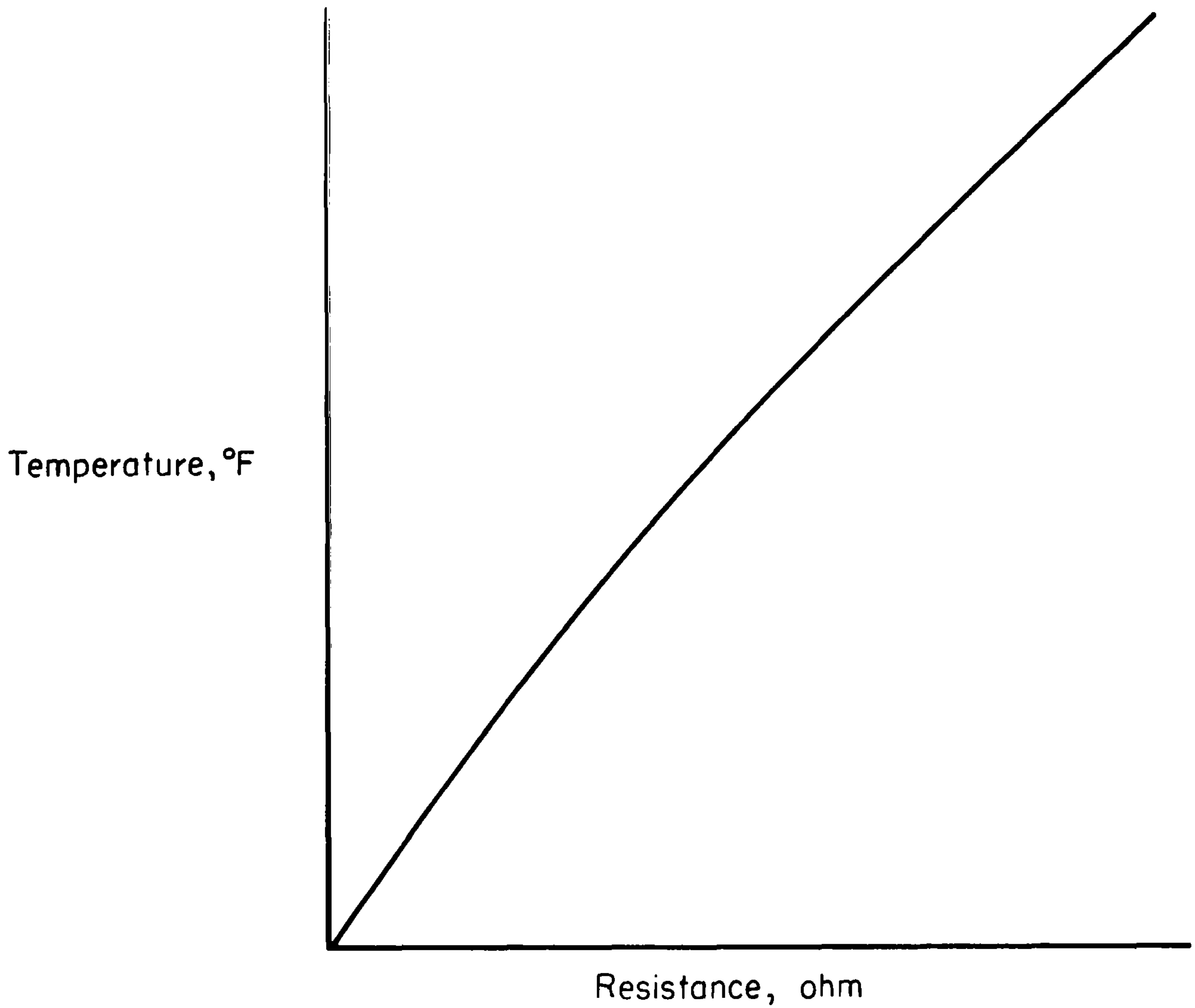


Figure 5.- Typical Army-Navy Specification (MIL-B-5495) curve for BN-1 resistance thermometers.

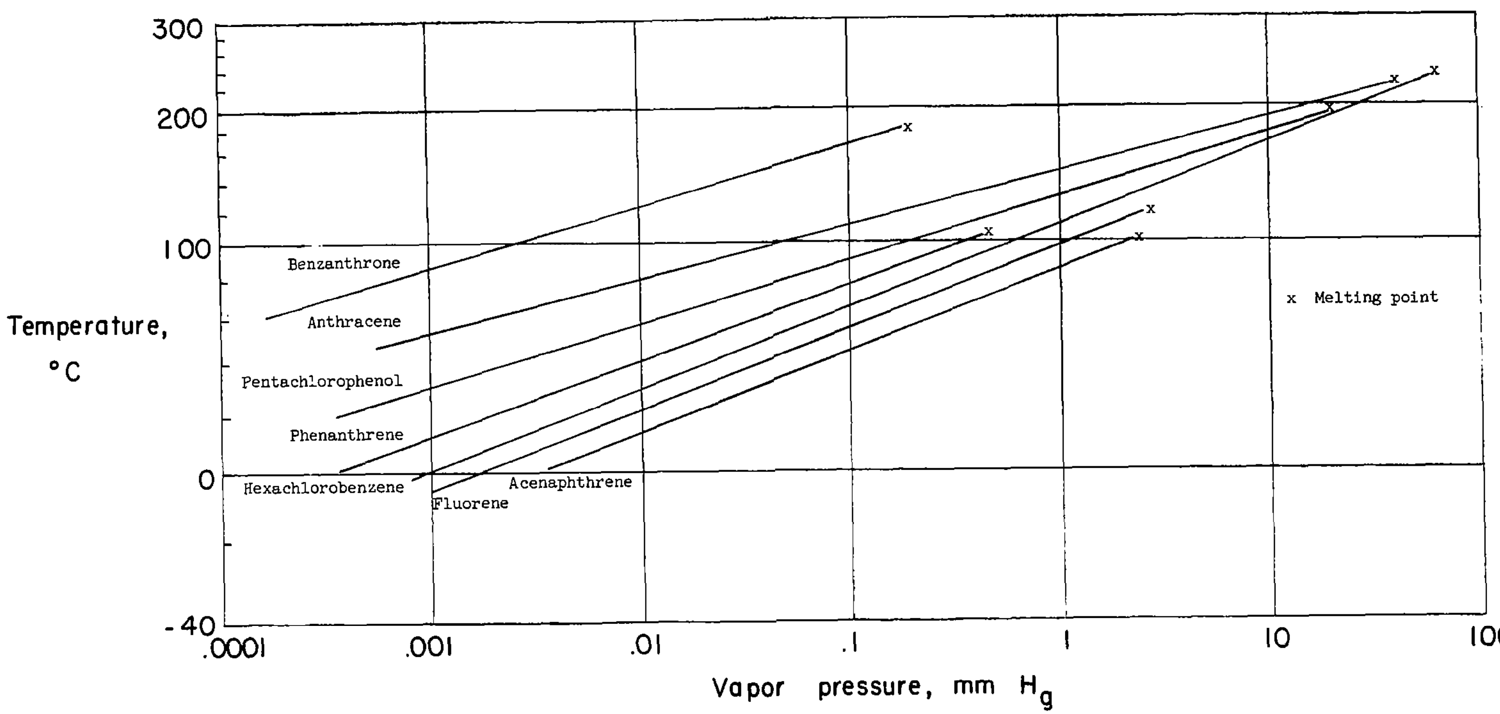
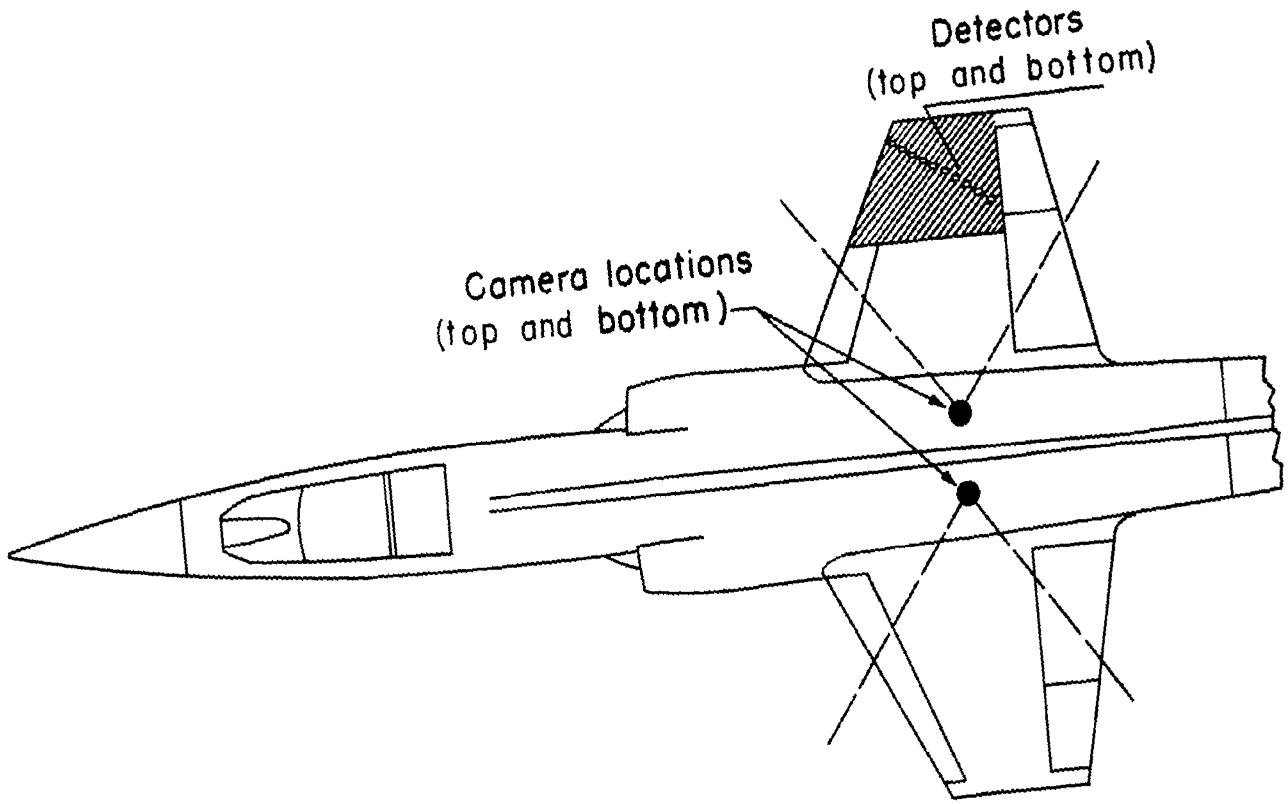
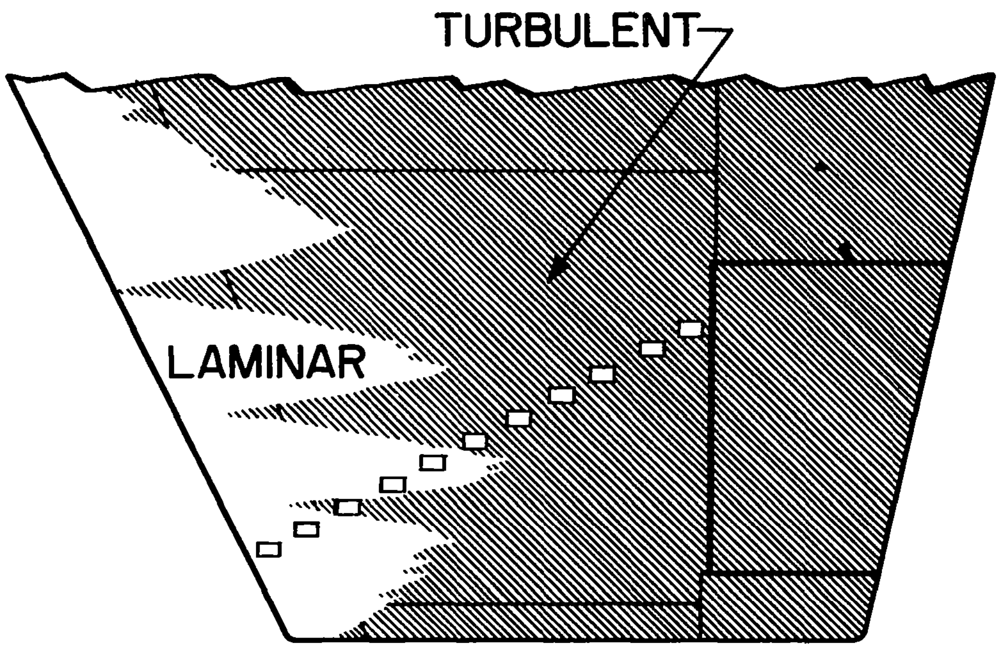


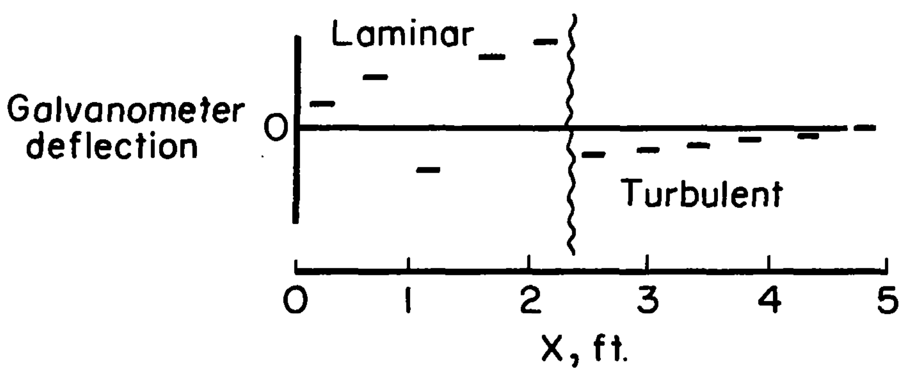
Figure 6.- Vapor pressure of sublimable chemicals.



...ment installation for detection of transition, showing location of cameras and detectors.



(a) Chemical sublimation technique.

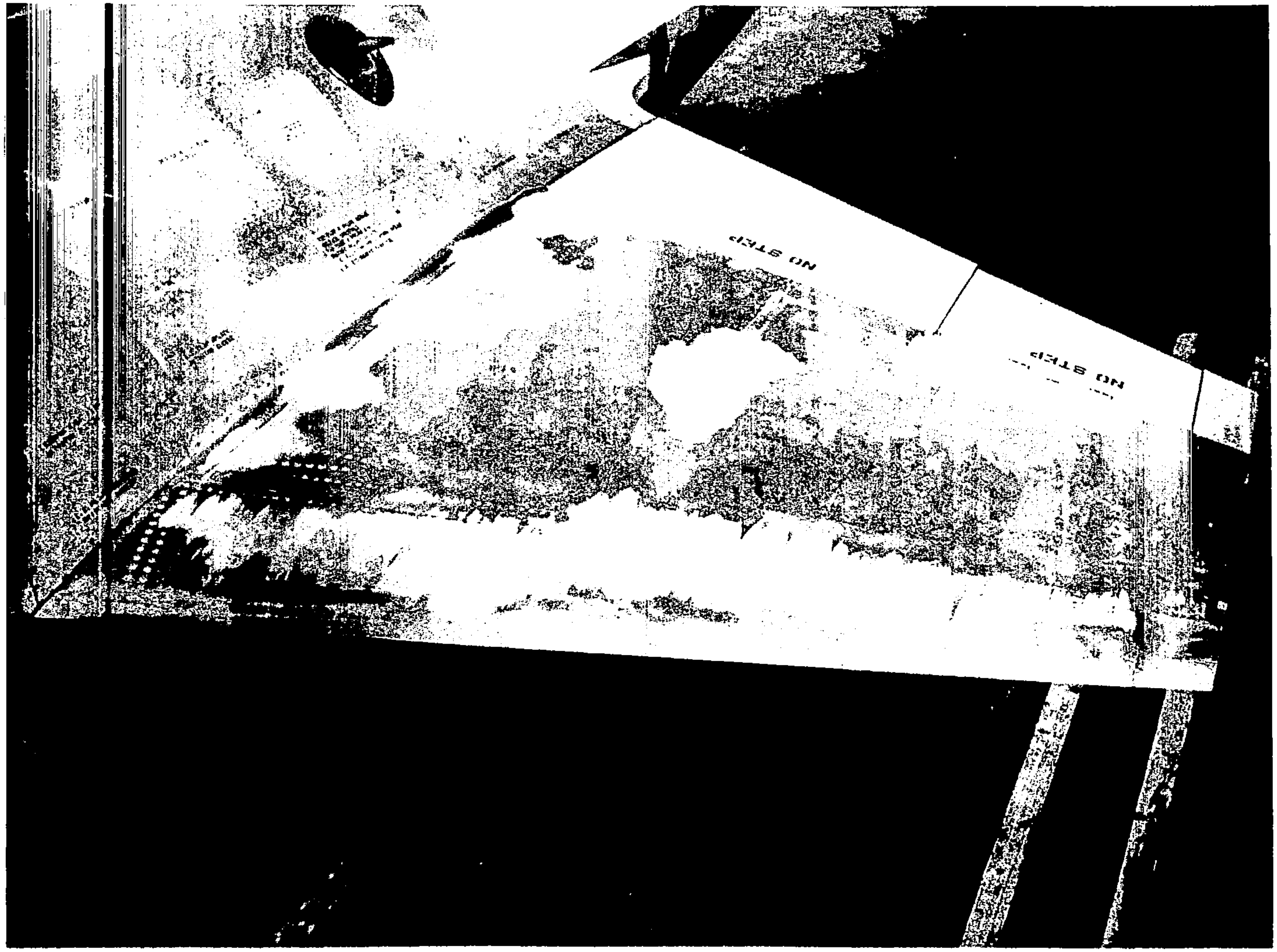


(b) Resistance thermometer technique.

Figure 8.- Sketch showing correlation of sublimation technique and resistance-thermometer method.

Figure 9.- Lower right-wing surface. Phenanthrene; M_{max} = 1.9; H_p = 55,000 feet. E-3460

Figure 10.- Top left-wing surface painted. Phenanthrene; $M \approx 1.8$; $H_p \approx 53{,}000$ feet. E-3513



E-3491

Figure 11.- Upper left-wing surface unpainted. Phenanthrene; $M_{max} = 2.0$; $H_p = 55,000$ feet.

Figure 12.- Upper right-wing surface. Fluorene; M_{max} = 1.8; H_p = 40,000 feet. E-3348

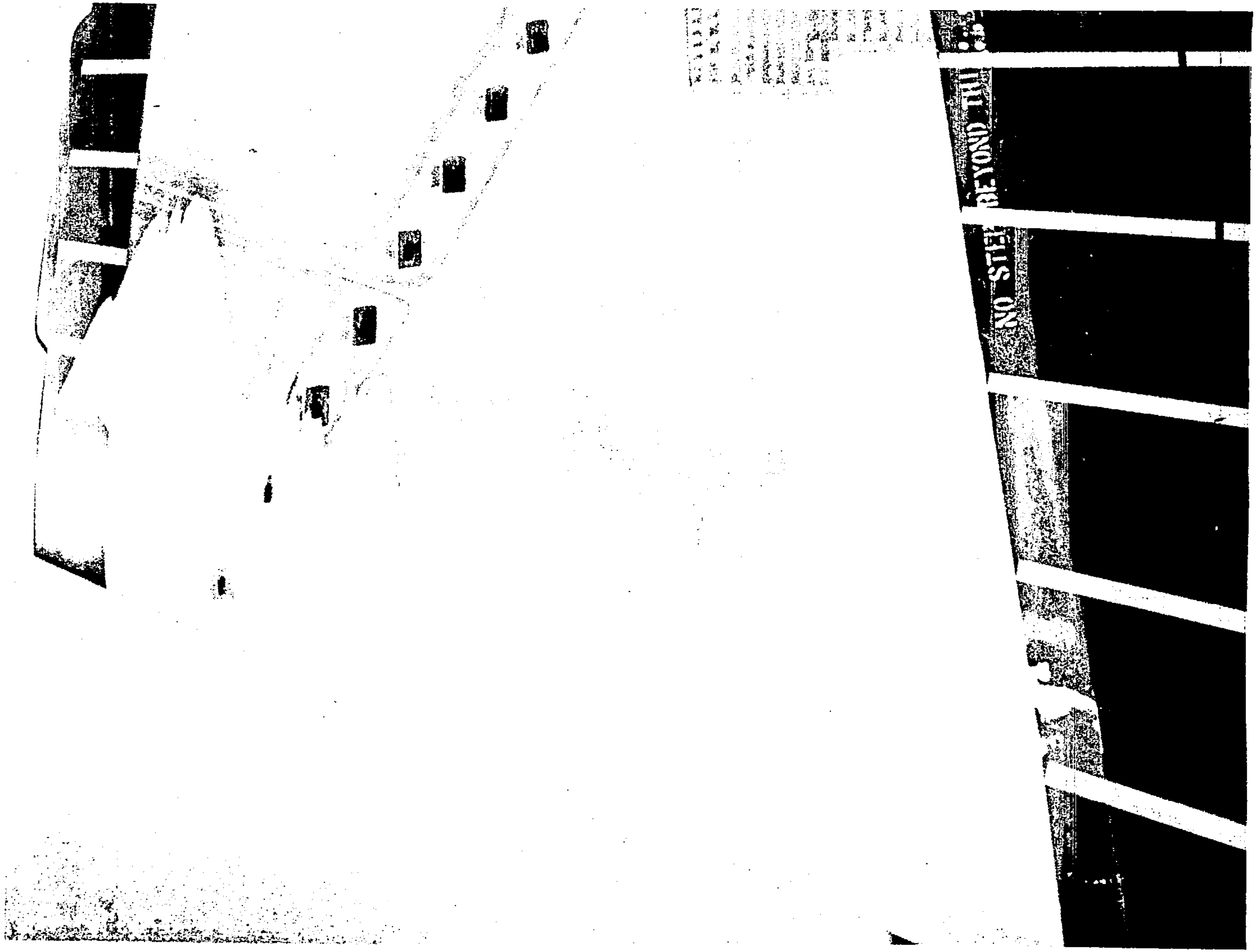
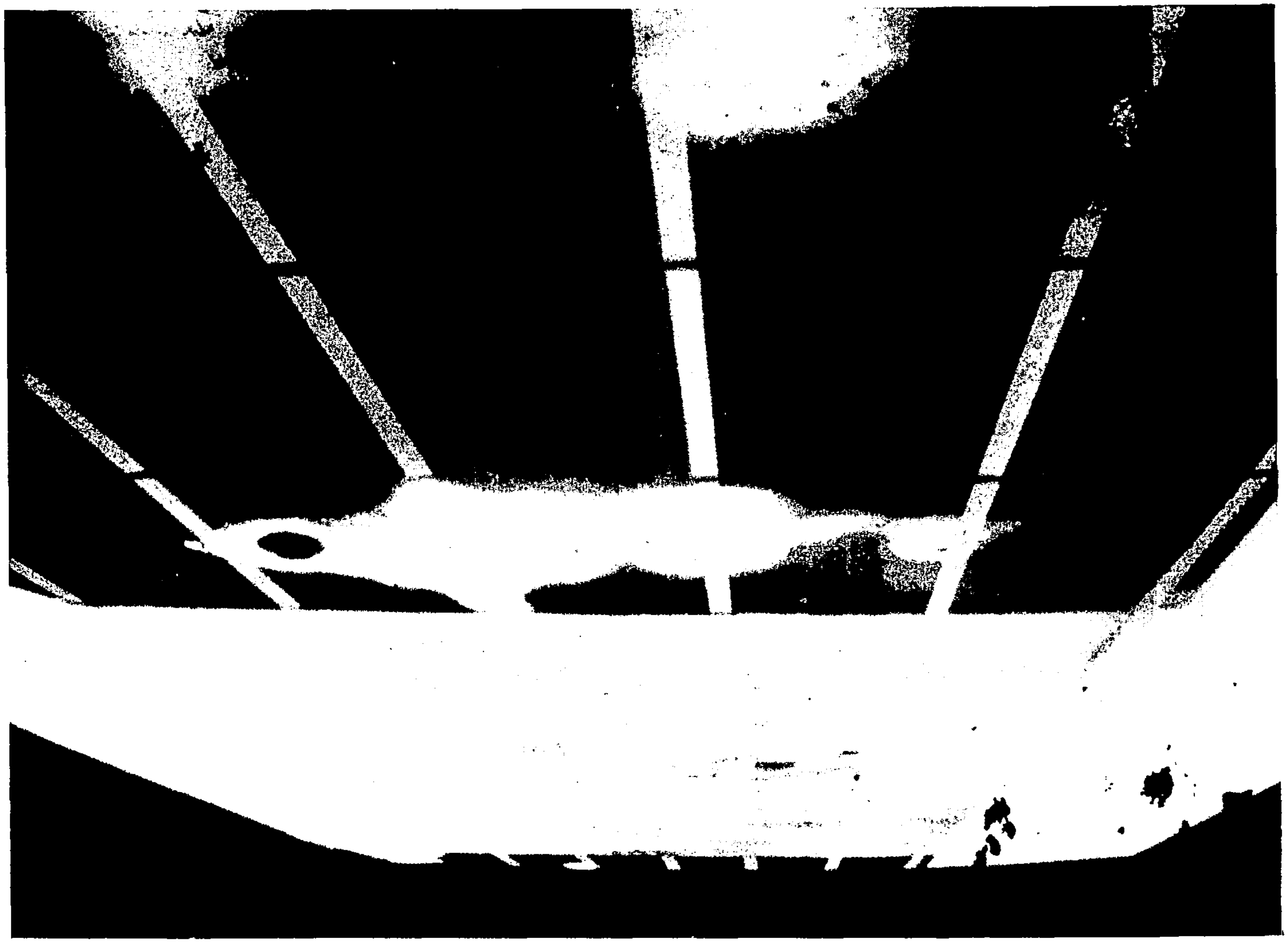


Figure 13.- Upper right-wing surface. Fluorene; $M_{max} = 2.0$; $H_p = 55{,}000$ feet. E-3355



E-3504

Figure 14.- In-flight photograph of bottom right-wing surface. Phenanthrene; $M = 1.9$; $H_p = 55{,}000$ feet.

COMMANDING GENERAL
AIR FORCE SPECIAL WEAPONS CENTER
ATT. SWOI
KIRTLAND AIR FORCE BASE, NEW MEXICO

T. N. D-18

1-4,7-1[illegible],16,17,20,21,23-25,27,28,
30-33,35,36,3[illegible],40-43,45,48,49,52,